WATER: A VALUE-ADDED PRODUCT

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"Over the coming decades, feeding a growing global population and ensuring food and nutrition security for all will depend on increasing food production. This, in turn, means ensuring the sustainable use of our most critical finite source: water"

Ban Ki-moon

UN Secretary General

Abstract

The objective of this paper is to proactively identify freshwater usage trends and supply throughout the agricultural- and food manufacturing industries in the United States. Fresh water is an expensive commodity for communities around the world as well as industries such as agriculture and energy, which rely on a continuous supply of fresh water. In 2014, amidst one of the worst droughts in state history, California invested $3 billion towards drought relief efforts to provide access to fresh water (Howitt et al., 2014). As nearly 20% of the world's irrigated agriculture supplies 40% of the global food supply, productivity and necessity promote the development of technological advancements in infrastructure for a reliable freshwater supply to agricultural producers around the world (FAO, 2014). However, overused fresh water for agriculture, surface, and groundwater pollution, as well as artificially deflated market prices from federal subsidies all limit freshwater conservation and the influx of new technology. In addition, freshwater resources are subject to anthropogenic activity limiting the viability of these water systems as potential clean water sources. Ecosystem degradation, groundwater depletion, water pollution, and irrigated land reallocation all play a significant role in limiting clean water sourcing. As of 2007, the United Nations declared that the global freshwater shortage was more important in influencing food security than access to arable land. As water insecurity increases, it is expected that the socioeconomic disparity between classes of people, those with and those without access to potable water, will increase. Farmland and property values will shift, and value/cost of water-intensive crops will continue to rise; this is evidenced as there have been 35 inter-state reported conflicts over water legislation and access rights in the period from 2000-2009 (Glennon, 2009). Proactive investment in water infrastructure, clean water initiatives, and water recycling have been inexorably linked to increased food security (FAO, 2014). The goal of this paper is to identify the impact of freshwater consumption by agriculture and food manufacturing industries on overall freshwater resources in the United States along with potential areas to decrease water consumption through technological advancement, economically driven market forces, and greywater recycling efforts.

About the Author

Andrew Tausz was born and raised in Westchester County, New York. While attending Stony Brook University, he worked as a wildlife educator for the New York State Parks at Wellesley Island, NY. After graduating with a B.A. in both English and Italian Literature, Andrew worked in a management role in an entrepreneurial restaurant start-up in Williamsburg, Virginia. After two years of restaurant management, Andrew continued his experience in the food industry as a Sauté Chef in Baltimore, Maryland. Realizing the potential for minimizing food and water waste in the food industry, he was encouraged to enrolled in integrated science classes at the University of the District of Columbia. These experiences inspired Andrew to pursue a Master's degree in Food Science from Cornell University, the top ranked school in the United States in this field.

Upon completion of the Master of Professional Studies degree at Cornell, Andrew will continue to pursue waste minimization in various sectors of the food industry through policy and grant writing. His future aspirations include influencing the food industry through consumer education. Andrew is a passionate cook and nature enthusiast in his personal life.

This report is dedicated to my parents, Linda and Tim who have always pushed me to pursue greater dreams,

to my aunt and uncle, Jodi and Dwight who taught me invaluable lessons and gave me incredible opportunities,

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List of Abbreviations

APC, Aerobic Plate Count

BOD, Biological Oxygen Demand

CCS, Carbon Capture Systems

CDC, Centers for Disease Control and Prevention

COD, Chemical Oxygen Demand

ECOSTRESS, Ecosystem Spaceborne Thermal Radiometer on Space Station

EPA, United States Environmental Protection Agency

EWG, Environmental Working Group

FAO, Food and Agriculture Organization of the United Nations

FDA, United States Food and Drug Administration

FRIS, Farm and Ranch Irrigation Survey

GRACE, Gravity Recovery and Climate Experiment

LCA, Life-Cycle Assessment

MAR, Managed Aquifer Recharge

MCL, Maximum Contamination Level

NASA, National Aeronautics and Space Administration

NIMBY, Not In My BackYard

SWDA, Safe Water Drinking Act

TKN, Total Kjeldahl Nitrogen

TOC, Total Organic Carbon

TSS, Total Suspended Solids

UNICEF, United Nations Children's Fund

UNDESA, United Nations Department of Economic and Social Affairs

USDA, United States Department of Agriculture

USGS, United States Geological Survey

VOC, Volatile Organic Compounds

WHO, World Health Organization

Useful Conversions:

1 gallon = 3.78 liters

1 hectare = 2.47 acres

1 acre = 43,600 ft^2 = 4040 m^2

1 inch of rainfall = 27,000 gallons per acre

1 cm of rainfall = 10 liters per m^2

km^3 = 264,000,000,000 gallons

1 acre-foot = 43,600 ft^3 = 326,000 gallons = 1,230,000 liters

Table of Contents

Introduction: Water as a value-added ingredient

The United Nations predicts that the global population will be 9.1 billion people by the year 2050. With limited agricultural space, ecosystem degradation, increasing populations, and social inequality, an intense focus on water resource management is needed to provide for the expanding global population. As estimated by the UN Food and Agricultural Organization (FAO), about 30% of the food produced worldwide is wasted, amounting to roughly 1.3 billion tons. Coinciding with this wasted product is an equally immense, underutilized, and geographically shifting water footprint. Of all the water consumed globally, the FAO estimates 70% of the consumption is used in the production of food. To understand the implications of a shifting potable water supply consider that the World Health Organization (WHO) in combination with the United Nations Children's Fund (UNICEF) estimated that only 71% of the global population (roughly 5.2 billion people) have access to a safely managed, accessible, and contaminant free, drinking water source (WHO and UNICEF, 2017). In addition, there are an estimated 850 million people without access to even a basic drinking source with 160 million of those people resorting to drinking water directly from surface water sources. This, combined with an estimated 2.4 billion people who are without basic sanitation infrastructure, is often the cause for widespread endemic diseases in these indigent areas (WHO and UNICEF, 2017). The UN Committee on Economic, Social, and Cultural Rights declared that, 'the human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses' (UNESCO, 2009). However, water and food security have significant economic implications considering that populations in developing areas spend 50-80% of their annual income on food (FAO, 2014).

As a finite resource, water is a necessary ingredient for all foods. Through germination, cultivation, harvest, storage, processing, consumption, and waste, water plays a critical role in the functionality of each step. It is important to take a multidisciplinary dynamic look at the entire life-cycle of water throughout food production to understand the individual challenges in water usage and conservation.

Investments are needed today for enhancing future food security; this requires action on several fronts, including tackling climate change, preserving land and conserving water, reducing the energy footprint in food systems, developing and adopting climate resilient crop varieties, modernizing irrigation infrastructure, reforming international food trade, and responding to other global challenges (Hanjra et al., 2010). Innovative technologies are required for sustaining food security, producing more nutritious food with less water (UN Water and Food Security, 2014). Improved crop yields, more efficient irrigation and fertilizer application, reuse of graywater of varying qualities, reduction of post-harvest and production losses, and more sustainable production of animal agriculture are all areas needing attention to improve water management (UN Water and Food Security, 2014). This literature study will focus on several of these water-related issues in the United States, providing a broad comprehensive overview of the challenges that affect water sourcing, conservation, and recycling. Water is often studied from a sustainability perspective and has economic, environmental, and social impact. This literature study will focus on the issues surrounding water sustainability in the United States, providing a broad overview of the challenges that affect clean water sourcing, conservation, and recycling.

Major areas of water consumption in the United States

The U.S. Geological Survey (USGS) was originally formed in 1879 as a part of the Department of the Interior. It was charged with the responsibility of studying the landscape of the United States, its natural resources, and potential natural hazards that threaten those resources. According to USGS data, irrigated agriculture and thermoelectric power are the dominant sources of water demand accounting for about 80% of the total water withdrawal in 2010 (Maupin et al., 2014). However, approximately 98% of withdrawals for thermoelectric cooling systems are returned to their source of origin while much of the water withdrawn for irrigation is consumptively used. Therefore, there is a particular focus by the USGS, in combination with the U.S. Department of Agriculture (USDA), on monitoring water resource availability and usage data for agricultural purposes. In the United States, an estimated 306 of the daily 355 billion gallons of water comes from fresh water, a surface or groundwater source (Maupin et al., 2014). Excluding thermoelectric power water withdrawals, agricultural fresh water use constituted about 61% of all other U.S. freshwater consumption in 2010. However, that same year, more than 50% of the total water withdrawals in the United States was accounted for by only 12 states with 10% being used by California's agriculture (Maupin et al., 2014). In July of 2012, California's governor, Jerry Brown, proposed a $24 billion plan for the Sacramento-San Joaquin River Delta that would restore habitat and improve the reliability of water supplies to the Central Valley and Southern California's coastal cities for both agricultural and domestic use (Culp et al., 2012). This proposal was for a levee system to mitigate saline and brackish water intrusion into the Delta. Today the Delta is protected by the implementation of the California Bays and Estuaries Policy and continues to supply piped irrigation and municipal water to much of Central and Southern California. The major agricultural producing states are responsible for the vast majority of freshwater consumption and taxpayer investments. It has been observed that groundwater reserves in some areas of the United States are being withdrawn at an average annual rate of 112 km^3 (Richey et al., 2015). Some of this water is replenished through deep soil percolation and natural processes, but the majority of these withdrawals are consumed. The USGS defines consumptive water use as "that part of water withdrawn that is evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (USGS, 2014). Thus, water consumption is the difference between the amount of withdrawal and the amount of water returned to a particular source. When interpreting data and statistics on water, it is important to distinguish between the amount of consumptive water and the water withdrawal rate. For example, only about one-half of the water used in irrigation is able to be recovered; the rest of this water is consumed in the agricultural process. In states with high agricultural production, irrigation can account for up to 90% of consumptive water use of both ground and surface-water resources (USDA, 2018).

The Bureau of Reclamation, as a part of the Department of the Interior, provides agricultural subsidies on the price of water and is the largest wholesaler of water in the United States (Edwards et al., 2012). It is often argued that these subsidies serve as an economic disincentive to motivate water conservation (Edwards et al., 2012). Subsidies on the price of water and political lobbying allow for large agricultural enterprises to receive water "welfare" and allow water-intensive crops to be grown in arid places like Arizona and central California. However, as the leading producer of food in the United States, California's agricultural production is critical to the national economy. About 30% of the nation's vegetables and 60% of its fruits and nuts were grown in California in 2012 (Kearney et al., 2014). Even more critical, California is an exclusive supplier of certain crops in the United States, producing 94-99% of the country's shelled almonds, olives, broccoli, and celery each year (Kearney et al., 2014). Despite current production, it is often argued that the economic sustainability of water subsidies is exaggerated by water's artificially low market prices, which fail to encourage water conservation (Edwards et al., 2012).

As a byproduct of excessive irrigation water use, agricultural runoff percolates into various groundwater and surface water sources which often causes salinity and contamination problems reducing their viability as a clean water source. Many of these contamination issues are rectified through expensive remediation projects. The dangers of agricultural runoff are strongly supported by evidence found by the USGS who reported that 20% of sampled aquifer wells used for drinking water were found to be contaminated from both naturally occurring and man-made contaminants (Desimone et al., 2014). Excessive nutrients, pesticides, and volatile organic compounds (VOC) have been infiltrating streams and groundwater as a result of various agricultural practices (Desimone et al., 2014). The phrase NIMBY stands for 'Not In My BackYard' and started as a result of community apathy towards environmental pollutants that occur in other geographical locations. As long as the problem does not directly affect them, communities accept ecological polluting practices with an 'out of sight, out of mind' mentality. This can excessively impact populations in low-income areas that may be ignored in their struggle against water scarcity. This concept applies to agricultural contaminates, updating wastewater treatment and storm-water sewer systems, and even unchecked corporate chemical spills. Water quality and quantity are both essential in assessing long term ramifications for the amount of water consumption versus its viable replenish rate, or the sustainability of a water resource (Berndt et al., 2015).

GRACE satellites and groundwater detection

Strict monitoring of groundwater stores and depletion is important to water recovery and conservation efforts, especially in areas susceptible to drought. Significant stress is placed on water resources primarily due to arable agricultural land, ecosystem degradation, increasing population, and higher standards of living (Richey et al., 2015). Proactive monitoring allows for potential water conservation policies to be enacted with sufficient data and, hopefully, a reasonable response time. The USGS started monitoring groundwater levels around 1950 and measures groundwater height using complex hydrological observations based on target area sampling of wells at specific sites. Through this sampling, it has been found that groundwater in specific crucial locations throughout the United States, specifically in the High Plains Ogallala Aquifer, has been steadily depleted for the past 50 years (Rodell et al., 2003). In addition, the complexity of accurately monitoring a large aquifer system makes it extremely expensive (Richey et al., 2015).

In light of this, in 2002 the National Aeronautics and Space Administration (NASA) and the German Aerospace Center collaborated to launch Gravity Recovery and Climate Experiment (GRACE) satellites (Long et al., 2013). The overarching goal of this program is to establish a time-lapse monitoring of climate trends, including precipitation variation and groundwater distribution over large areas. Calculating data over varying time scales, GRACE satellites can monitor minute changes in gravitational pull to quantify the mass of groundwater at a specific location. The greater mass present in a particular area, the greater the gravity of that area. This technology allows NASA scientists to monitor groundwater depletion in comparison to its regeneration rate through monitoring water redistribution over time. By measuring slight variances in gravitational pull from a particular area before and after a period of rainfall or drought, the satellites are able to create an accurate measurement of moisture migration. This type of measurement provides a more accurate overview of withdrawal when compared to disaggregated soil moisture and conventional groundwater monitoring methods (Long et al., 2013). With an accuracy of ± 1.5 cm of equivalent rainfall height, it has been observed that U.S. groundwater systems have an average withdrawal rate of 112 km^3 per year (Richey et al., 2015). On the other hand, recharge rates are also taken into account. For example, during the 2011 drought in Texas, GRACE satellites observed a water consumption of 62 ± 18 km^3 of total groundwater water between the Ogallala and Edwards Aquifers (Long et al., 2013). To put this in perspective, one km^3 is the equivalent of 264 billion gallons of water. The 2011 drought had an extremely significant effect on the increased consumption of groundwater throughout Texas and cost the state an estimated $7.6 billion in agricultural losses (Long et al., 2013).

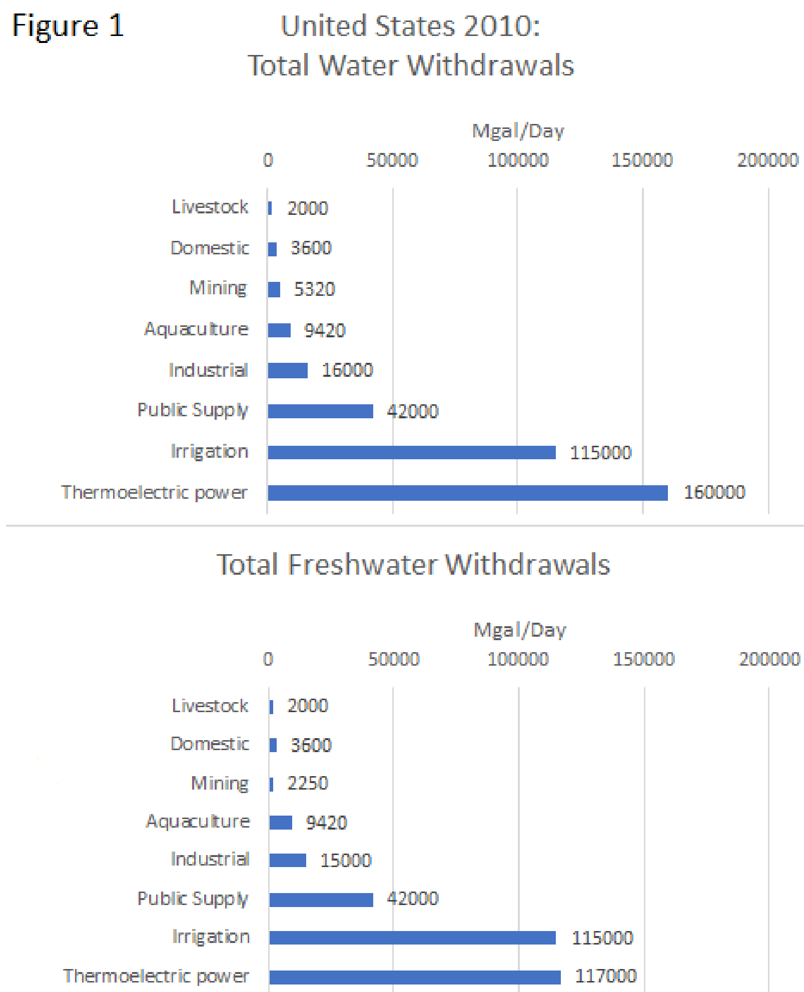
The GRACE satellites collected data on gravitational mass shifting from low earth orbital position at a measured varying distance of approximately 200 km between satellites. The mechanism for detecting the distance between these two satellites is affected by temporal changes in the gravitational pull relative to shifting mass variances of three primary factors: surface reservoir storage, soil moisture storage, and groundwater storage. It is GRACE's ability to detect groundwater at all three levels that sets it apart from other satellite imaging using radar or radiometer to detect only surface-level water distribution. This quantification is termed the 'Renewable Groundwater Stress Ratio' and calculates the rate of groundwater withdrawal versus viable recharge (Richey et al., 2015). A high Renewable Groundwater Stress Ratio indicates an area being rapidly depleted of its groundwater reserves. However, withdrawal and consumption rates do not entirely depict aquifer and groundwater functionality. The GRACE satellite data is used in conjunction with a statistical predictive model that allows scientists to calculate the Renewable Groundwater Stress Ratio based on water withdrawal rate and does not account for dynamic stresses placed on the groundwater source in response to geological shift and anthropogenic activities (Richey et al., 2015). Soil and clay compaction causing land settling, natural toxicants, agricultural runoff, and rising salinity levels are all examples and major contributors in limiting the viability of groundwater sources. In addition, aquifer water quality studies are based on hydrogeology of the aquifer and not overlaying land use, which would be indicative of potential groundwater contamination (Desimone et al., 2014). The GRACE mission lasted from 2002-2017 gathering information on global groundwater data trends. Despite its limitations, one of the most significant observations from the GRACE data is a shifting movement of water towards more extremes in precipitation distribution - dry areas facing greater drought and humid/wet areas facing greater flooding. NASA recently launched its new Ecosystem Spaceborne Thermal Radiometer on Space Station (ECOSTRESS) satellite that detects variances in plant heat signatures. Using this technology, scientists will have an advanced monitoring system for agricultural water consumption and improved drought estimations based on water uptake from crops and their consequential temperature. As plants remain adequately hydrated, they release water to evapotranspiration, which lowers the temperature of the plant. Monitoring these temperature ranges can determine if an area needs more or less water application.

Thermoelectric power

The focus of this paper will largely center on agricultural uses of water, but, when taking into account a comprehensive overview of water withdrawal rates, traditionally, agriculture and thermoelectric power are the largest users of water in the United States. This is because thermoelectric equipment cooling is responsible for about 41% of the total national water withdrawal, used to condense large quantities of steam, which is generated by turbine generators (USDA, 2018). For this process, 91% of the saline surface water withdrawals in the United States are used in thermoelectric power plants (Maupin et al., 2014). This statistic may be indicative of a highly underutilized resource as desalination is used in other countries with limited freshwater resources. In addition to using saline water for thermoelectric power regeneration, through careful implementation of reverse osmosis technologies, these surface waters can also be used to supplement an agricultural or potable freshwater supply. In Israel for example, about 41% of its total potable water supply comes from saline water sources, supplying 34% of its agricultural production (Tenne, 2010). The design of desalination operations provides significant opportunity to reduce the amount of freshwater intake through technological advancement (Pan et al., 2018).

In looking solely at thermoelectric power, because of a delicate balance between thermoelectric water demands and surface water supply, there are many challenges in implementing changes to political policy. Legislative changes need to establish ecologically safe, consistent, and sustainable water sources for thermoelectric power plants, so that withdrawn water can be recycled back into natural water reserves without detrimental ecological impact (Pan et al., 2018). Large amounts of energy are needed to pump, treat, transport, heat, cool, and recycle water. In turn, water is used for generating power as steam to turn electrical turbines and is the primary cooling fluid used to condense this steam (Pan et al., 2018). To highlight the delicate balance between power production and water withdrawals, carbon capture systems (CCS) have been proposed to reduce the total carbon emissions from thermoelectric plants. CCS can be implemented in various ways; however, regardless of the system used, using CCS greatly increases the amount of water needed with thermoelectric power for cleaning and condensation of the heated CO_2 gas (Chandel et al., 2011). It has been predicted that by the year 2035, because of increasing energy demands, thermoelectric power generation will have an unsustainably enormous water withdrawal rate if proactive investments are not made in the renewable energy sectors such as solar, wind, hydropower, and geothermal energy (Pan et al., 2018). Despite some of the ecological impacts and demands from thermoelectric water withdrawal and its effluent, about 98% of withdrawals are returned to their source of origin. Therefore, even though thermoelectric power generation has greater withdrawal rates than agriculture, it has a much smaller water consumption rate and overall impact on freshwater stores, with 50% of agricultural withdrawals being consumed (USDA, 2018).

Figure 1



Maupin et al., 2014

Agriculture

Agricultural irrigation accounts for 38% of the total freshwater withdrawals or an estimated daily amount of 115 billion gallons in the United States (Maupin et al., 2014). This is more than double the 42 billion gallons per day (Fig. 1) or 14% withdrawn by the public water supply. Excluding withdrawals for thermoelectric power, agricultural demand represents about 65% of the total freshwater withdrawals in the United States (Maupin et al., 2014). Agricultural water is water that is used to grow fresh produce and sustain livestock. Currently, irrigation sources about 57% of its water withdrawal from surface water and the remaining 43% from groundwater (Maupin et al., 2014). This distribution varies widely from state to state, time of year, and climate conditions. As surface water and precipitation run dry, heavier reliance is placed on groundwater to sustain irrigation. Groundwater withdrawals from the states of California, Arkansas, Nebraska, and Texas accounts for 42% of the total national withdrawal (Maupin et al., 2014). It has been found that water conservation programs vary widely based on local hydrologic factors, the type, size, and location of irrigated farms, and the legislation governing water use (USDA, 2018). Thus there is a USGS measured response to dynamic irrigation needs across the United States. Farmland demand for irrigation changes over time in response to water resource and agronomic conditions, climate and season, and crop-specific market demands (USDA, 2018). To stress the significance of irrigated cropland in food production, in 2012 irrigated farms produced 50% of the total sales in the United States on only 28% of harvested farmland, showing a heavy reliance on irrigation for a consistent food supply (USDA, 2018). Despite the enormous need for more efficient production of food with better management of water resources, irrigated acreage in the United States is declining. The cost of updating inefficient irrigation systems and shift to a drier climate has caused a major decline in irrigated acres across the United States. In the period from 2007-2012 there was a decline of 0.8 million acres of irrigated farmland driven by drought conditions and water scarcity (USDA, 2018). In addition, various data estimating consumptive-use may not be entirely accurate. Water consumption estimates need to consider system efficiency losses such as evaporation, deep soil percolation, and agricultural runoff, along with geographic location, crop selection, and type of irrigation system (USDA, 2018). Governmental policy on water use should consider both the macro perspective driving market forces of viable water resources and the micro perspective of local constraints and challenges facing water conservation in a particular region. This more dynamic overview of irrigation and agriculture is necessary to promote water conservation. Across the United States there is a predicted temperature increase of 5°-7°F over the next century accompanied by a 7-27%

decrease in stream flow for several prominent river basins including the Colorado River, the Rio Grande, and the San Joaquin River (Bureau of Reclamation, 2017). If proactive investments are not made to improve irrigation and sustain current producers, than impending water scarcity could have serious ramifications on both the food supply and economy in the coming years.

Highlighting some of the efficiencies of various irrigation systems, USDA and USGS have done aggregated measurements on different types of irrigation systems to find average water withdrawal and application requirements. Once every five years, a Farm and Ranch Irrigation Survey (FRIS) is sent out to collect data from individual producers requesting information on water sources, amount of water used, irrigated acreage, type of irrigation system, yield by specific crop, any system investments from the producer, along with energy costs (USDA Census of Agriculture FRIS, 2017). These data are intended to serve as an analytical tool for water usage trends, technological advancements, and assessment of legislation. From the 2013 survey, 35,000 producers using irrigation responded. The data showed that water application rates in the western states averaged 2.3 acre-feet for gravity systems, almost double the 1.2 acre-feet of water for sprinkler systems based on the information provided by the users (USDA, 2018). An acre-foot is the equivalent to one foot of water over one acre, which is ~326,000 gallons of water, showing the vast difference in the efficiency and total water applied between gravity fed and sprinkler systems. The overarching types of irrigation: flood/gravity fed, sprinkler, and micro-irrigation have all been compared to analyze their efficiency and economic viability. Micro-irrigation or drip irrigation are systems that look to minimize water evaporation by applying small quantities of water directly to the root zone of the plants. It has been determined that the maximum efficiency for flood/gravity fed systems is 70-85% of the total water applied, for sprinkler systems is 70-90% (depending on increased rate of evaporation due to wind), and for micro-irrigation systems is 80-90%. This means that the minimum amount of water lost in all of these systems is at least 10% (Hanson et al., 2004). Despite higher capital investments in the period between 1990 and 2000, there was a 20% decline in California in the use of flood/gravity fed irrigation systems that were replaced by micro-irrigation systems. During this time period the use of sprinkler irrigation systems remained static (Hanson et al., 2004). In addition to reduced water withdrawal and consumption, the greatest benefit of more efficient irrigation systems, or localized fertigation, may be improved water quality, mitigated saline soil intrusion, and less agricultural runoff of pesticides, nutrients, and sediments (Elfers et al., 2015). Fertigation is the practice of applying fertilizer directly through an irrigation system to increase plant uptake and decrease excess runoff. Saline soil intrusion is the buildup of salts over time that render smaller crop yields because the hydrophilic nature of these salts allows for less available water to be absorbed by the roots of the plant. Irrigation water transports these ions in small quantities, which, over time, increase the sodicity of the irrigated soil. Despite the scientific evidence for improved irrigation systems, more than half of irrigated cropland acres uses traditional, less-efficient application systems (USDA, 2018). The FRIS data indicated that the potential exists for increased irrigation efficiency through updated water-management practices. It has been found that fewer than 10% of producers use soil or plant-moisture sensing devices and less than 2% use computer-based simulation models to determine irrigation requirements accounting for crop selection needs and current climate conditions, showing the potential need and, hopefully, eventual demand for an influx of technological advancements in the agricultural sector (USDA, 2018).

Conservation through technological advancement is only one hurdle in improving water management practices. The allocation of water rights to specific reserves of groundwater creates water use competition among farmers, the local communities, and a limited clean potable water supply. For example, the High Plains Aquifer or Ogallala Aquifer in the central U.S. supplies about ⅓ of the total groundwater used for irrigation, supplying predominately center-pivot sprinkler irrigation throughout this region (Desimone et al., 2014). As demand for irrigated agriculture increases in the central Mid-west states, the groundwater reserve of the Ogallala Aquifer is being withdrawn at an annual average rate of 2 feet per year and is naturally recharged to only 0.5 inches per year (Elfers et al., 2015). Despite the known rate of consumption, there is a culture of water competition instead of water conservation. Producers looking to conserve water would find themselves in a situation of unilateral economic disarmament while neighboring farms seek to maximize their profits through increased water usage (Elfers et al., 2015). Investment in water conserving technologies or management strategies creates a profit margin among producers guzzling the last reserves of a vital aquifer. This 'tragedy of the commons' situation has been used in hydrological models to predict that certain parts of the Ogallala Aquifer will be completely emptied of groundwater in the next 15-20 years (Elfers et al., 2015).

Further west in the United States, the agriculture industry threatens local communities with water scarcity. Private wells are often run dry by surrounding agriculture with access to deeper groundwater reserves. There have been substantial migrations of people from areas in Southern/Central California where populations are supplied potable water using transport trucks. This water comes from surrounding area municipal mains water because these residential areas, reliant on well water, do not have a piped supply of water. Ecosystem degradation due to agricultural land reallocation in these areas has led to widespread over-consumption of community groundwater (Elfers et al., 2015). Domestic and public use combined account for about 46 billion gallons per day of water withdrawals and the average U.S. domestic water use is about 100 gallons per person per day; this quantity can vary by 50% depending on the part of the country (Maupin et al., 2014). The western more arid states often have higher daily averages of gallons per person because of increased personal water use in consumption, sprinkler systems for lawns, and general increased need for greater quantities of water. The population of these states is expected to rise 35-45% by 2040, showing the need for remediation of water access rights (Kearney et al., 2014). Currently 86% of the U.S. population receives its potable water from a public supply with the remaining 14% (100-140 million people) of the population being self-supplied from groundwater (Maupin et al., 2014). Under the Department of the Interior, the Environmental Protection Agency (EPA) designates safe drinking water quality parameters through implementation of the Safe Water Drinking Act (SWDA). All matters regarding public and potable water supplies must comply with these drinking water standards; a public drinking water supply is defined as any “water for human consumption through pipes or other constructed conveyances to at least 15 service connections or serves an average of at least 25 people for at least 60 days per year.” According to the 2008 EPA estimate, 15 million people in the United States have private drinking water wells that are not considered a public supply and are therefore subject to no regulations or auditing. Of the millions using well-water in the United States, many are water scarce due to resource availability or potential contamination and may not even be aware of their situation.

Highlighting the potential environmental impact of agricultural practices is the external cost of ecosystem cleanup. In the United States, ecological remediation of agricultural damage caused to people and the environment has an estimated annual cost of $9-20 billion (UN Water and Food Security, 2014). This severely limits the economic viability of certain water sources entirely. In 2010, the USGS performed a series of tests on groundwater sampling wells. Of the thousands of wells tested, 22% were found with chemical constituents at a concentration greater than the EPA maximum contaminant level (MCL) standard for drinking water (Desimone et al., 2014). Samples for this study were collected at the wellhead prior to treatment so they would not be indicative of tap water quality for the public supply, but remain unmonitored for millions of people primarily using a private groundwater drinking water source. These contaminants come from natural geological shifts and elements contained in the aquifer system along with those used in agriculture, industry, or even by the public (Desimone et al., 2014). The predominant forms of anthropogenic contamination are excessive nutrients, pesticides, and VOC that are able to easily move through the water column into groundwater. Irrigation causes a number of problems in river systems as well. Irrigation runoff from fields flows back into rivers, picking up various contaminants and nutrients that later may cause algal blooms like those seen in Lake Erie, coastal waters around San Diego, the Ohio River, Rio Grande, the Colorado River, the Chesapeake Bay, the Gulf of Mexico, and Lake Okeechobee just to name a few. More investments are made retroactively, trying to remediate agricultural practices, than proactively, trying to reduce the initial irrigation runoffs and mitigate ecological impacts (Edwards et al., 2012). The sustained quality of water resources and ecosystems depends directly on the data and development of science-based policy influencing management practices (Desimone et al., 2014).

The economics of water conservation

As shown, in arid western states, a lack of precipitation creates dependence on surface water and groundwater supplies. In areas where these resources are lacking, water is piped over hundreds of miles. Agricultural producers are able to grow water-intensive crops in parts of Arizona or Central/Southern California because of this transported water system. One example would be The Central Arizona Project, which pumps water up 3,000 vertical feet and across 160 miles of arid land from the Colorado River to central Arizona with an estimated completed project cost of $4.7 billion (McMaken, 2003). These areas continue to become more densely populated with agricultural producers and irrigated acreage. In 2013, about $2.6 billion was spent on irrigation facilities in the United States with 72% of these investments made on land in the western states where irrigation continues to be concentrated (USDA, 2018).

This seeming water phenomenon is made possible through federally subsidized water for agriculture that continues to grow crops in climate conditions that could not support similar production with a free market economy (McMaken, 2003). It is often argued that these water-intensive crops grown in arid western states compete with more efficient production of the same crops in other parts of the country simply because they are backed by a federally deflated price of water. On average almost $90 million a year in water subsidies are allocated to grow just cotton and rice in the Mid-west (Edwards et al., 2012). These subsidies on the price of water are set and regulated by the Bureau of Reclamation, which is the largest wholesaler of water in the nation and, because of its access to water, is the second largest producer of hydroelectric power, with 58 plants (Edwards et al., 2012). In terms of water quantity, but also subsidy percentage, farmers are the primary beneficiaries of federally subsidized water, where this resource is distributed not by market price, but by a political process (McMaken, 2003). Whereas changes in water rights (first priority to subsidized water), water transfers between legislative entities (control of water sources), and market pricing would all promote more efficient management practices, the heavily subsidized price of water allows producers to ignore conservation efforts (Edwards et al., 2012). Rights to water in many parts of the western United States were previously doled out under a legal system known as prior appropriation, which granted the first user of the water the right to continue using it (Culp et al., 2012). Through prior appropriation, grandfathered agricultural users hold water rights over local communities, industry, and even other, potentially more efficient, producers. Farmers who do invest in conservation efforts are not able to use, lease, or sell the water they save as this resource is typically passed along to and guzzled by the next junior user (Culp et al., 2012). This allows larger irrigated farms, under prior appropriation, to receive a certain 'corporate welfare', allowing producers to bypass market prices linked to water quantity consumed and the transportation infrastructure costs. Consequently, efforts to conserve water or invest in water saving technologies are not incentivized as they would be in a free market economy (McMaken, 2003). Those in favor of water subsidies argue that the price reduction allows for already established farmers to continue to produce crops in these arid areas, providing jobs and supporting the local economy. Although there are strong arguments both for and against subsidies with quite a bit of gray area regarding the efficacy of this economic cushion, it seems that water availability and future trends towards sustainable water management practices will be a limiting factor in subsidy allocations.

In the case of The Central Valley Project (California) about 6,800 producers use subsidized irrigation water. This is the Bureau of Reclamation's largest irrigation project supplying water to irrigate roughly 3 million acres of land (Edwards et al., 2012). However, these producers purchase this piped fresh water at 10% of its market value, which equates to $400 million a year in total subsidies (Edwards et al., 2012). The Environmental Working Group (EWG) is a non-profit, non-partisan organization that monitors scientific research in the areas of food, water, and energy production in the United States, specializing in research regarding toxicants, agricultural subsidies, and corporate accountability among others. It has estimated that those producers receiving water subsidies, also receive additional subsidies on electricity and crops worth over an additional $100 million a year (Edwards et al., 2012). In 2011 alone, the Bureau of Reclamation had a net budget outlay of $2 billion (Edwards et al., 2012). Yet, in 2013, it was found that 90% of farms reporting irrigation improvements received no public financial assistance, with only 24% of the total reported improvements being made to enhance water management practices. The remaining reported investments were made to reduce energy costs and conduct annual maintenance (USDA, 2018). This slow response to an ever increasing problem of mitigating a depleting water resource has been cited as a product of an aging infrastructure, shifting climate, and taxpayer funded boondoggle projects (McMaken, 2003). Consequentially, the concept of a decentralized infrastructure and decision making authority may promote more unique approaches to individual local water issues that may not be economically, environmentally, or socially beneficial to implement on the federal level. In addition, reductions in subsidies may reflect more accurate market prices and promote reform to both federal and state water policy and proactive conservation efforts (Edwards et al., 2012). However, this increase in the price of water could have dramatic effects on the price of the current food supply; products would more accurately reflect their respective water footprint.

In addition to local market driven forces, international trade enables consumptive water use to be transferred across national boundaries, known as the virtual water trade (Wan et al., 2016). The virtual water trade is responsible for the about 10% of non-renewed groundwater withdrawals of the United States, Mexico, China, and Iran, countries particularly exposed to water risk management because they both produce and import food irrigated using rapidly depleting aquifers (Dalin et al., 2017). In 2012, the western United States shipped 50 billion gallons of water, a quantity estimated to supply the annual needs of 500,000 families, to China in the alfalfa crop that was destined for animal feed (Culp et al., 2012). Due to local market prices in the United States and international trade laws, it currently costs twice as much to truck crops from a Southern California farm to California's Central Valley as it does to ship that same crop from Long Beach, California to Beijing, China (Culp et al., 2012). Efforts are currently being made by various organizations to analyze the movement of virtual water, identify various global regions at high risk for depleting their water resources in this manner, and the final consumers of various water-intensive international products (Dalin et al., 2017). However, it is difficult to assess the international virtual water trade among nations. This is because hydrological records are often withheld from the public for socioeconomic, political, and defense reasons (Famiglietti et al., 2013).

Managed aquifer recharge

Seawater desalination has been explored as a technology to produce fresh water since the 1950s. It has been implemented in countries around the world to alleviate natural freshwater stresses in arid climates and remains a viable option that is expected to increase in use over the coming years. However, desalination still remains an energy intensive approach to providing fresh water and there are potential environmental concerns associated with both the energy usage and the briny effluent produced in the process (Elimelech et al., 2011). Despite these challenges, there is continued research to develop advanced technologies to improve performance flux of the desalination membranes (as a result of energy demands) and the environmental sustainability of using seawater desalination as a solution to water shortages (Elimelech et al., 2011). Looking at alternative approaches to augmenting the freshwater supply, the concept of managed aquifer recharge (MAR) was first practiced in Australia. Instead of relying on natural rates of recharge, MAR may be sourced from rainwater, storm water, reclaimed water, or even other aquifers as a way of balancing ever-increasing withdrawal rates (Dillon et al., 2009). This is accomplished through various mechanisms such as injection wells, and infiltration basins for rainwater, storm water, reclaimed water, and mains water. Controlled recharging of aquifers during surplus conditions has proven to be one of the cheapest ways to amass water for drought emergencies. That being said, studies have shown that MAR is subject to an economies of scale. This means that smaller operations are not as economically profitable as larger operations, measured in cost per unit volume, when compared to mains water (Dillon et al., 2009). This is to say that the cost of municipally supplied public water is more expensive per unit volume than large-scale implemented MAR operations. It has also been found that storm-water utilized for recovery and storage has an average levelized cost, looking at all implemented operations across Australia, that is 30-45% less than seawater desalination, water treatment, or water recycling plants (Dillon et al., 2009). Despite the economic benefits, MAR efficacy in water management is highest when applied in conjunction with other water conservation measures to maximize efforts based on seasonal peak water demands and may additionally have significant environmental benefits.

One continuing area of concern is soil compaction due to overdrawing an aquifer. Once large quantities of groundwater are withdrawn, there can be substantial ground sinking and this compacted earth cannot recover the same water-holding capacity (Elfers et al., 2015). This occurs most dramatically in clay soils, but all soil types are affected by extreme withdrawal rates. In the United States, parts of the west have adopted several MAR strategies, like those seen in areas of California and Idaho, but there remain many improvements to be done in the way of establishing large-scale groundwater recharge.

Life-cycle assessment and animal agriculture

A standardized methodology for the life-cycle assessment (LCA) of products is currently being explored. The purpose of LCA is to connect all potential environmental burdens, especially resource and energy utilization, with the processing of a particular product from raw material through waste removal or repurposing. This concept is centered around acquisition of accurate producer data and uses various modeling systems to predict environmental impacts of particular products with an appropriate confidence level to accurately influence policy decisions around those products (Poore et al., 2018). This type of modeling includes producers from around the world and accounts for varying growing conditions accordingly. Accurate and standardized LCA data can be an effective tool for larger organizations looking to add product water footprint labeling. It is important to note, however, while the water footprint has implications for land and energy use, it does not reflect the LCA in those areas. A balanced assessment is required on each of these issues when looking critically at a LCA, something few assessments actually have accomplished.

One common example of a LCA, animal agriculture is often pointed out for its inefficiencies in both water and land use. Livestock freshwater withdrawals are estimated to be the smallest category as established by the USGS, of water withdrawal in the United States, using about 2 billion gallons per day (Fig. 1). However, it has been found that global animal production contributes to about 30% of the water footprint with the majority of this water, about 98%, being consumed in the production of animal feed and not by the animals themselves (Hoekstra, 2012). Included in this water footprint of animal agriculture is crop cultivation, livestock farming, food processing, retailing, and consumption. However, this assessment of water footprint fails to consider the implications of certain land requirements. Ruminant animals have the unique ability to convert grassland into feed; using grassland that should not be plowed creates greater efficiency in producing food. However, more industrialized countries, like the United States, with a diet centered largely around animal products, could potentially reduce their respective water footprint up to 35% by converting to a vegetarian diet (Hoekstra, 2012). The FAO estimated that 40% of the cereal crops produced around the world were used for animal feed in 2007. This is hardly surprising considering that protein derived from animal products accounts for roughly 40% of the total human protein consumption (Boland et al., 2013). Despite this significant quantity of protein consumption, the average water footprint (which includes feed production) to produce a calorie of beef is 20 times larger than that of cereal and starchy root crops (Hoekstra, 2012). However, as mentioned before, this statistic does not define arable land applications (areas where the ruminant animal would efficiently convert non-arable land into food), the use of plant by-products by ruminant animals, and it does not reflect energy usage requirements to produce the same calories of food. For example, the act of cooking these products creates varied energy requirements - where beef may be quickly cooked, often cereals and starchy root crops require longer cook times and, consequentially, extra energy inputs. This logic also presumes to measure the water footprint of these products in terms of calories produced and is not based on the nutritional value of those products.

When assessing the water footprint of animal agriculture, the social and ecological impacts of water use at any particular location depends on the water availability and potential alternative uses of water at that location. Because of an ever increasing social standard of living, however, and demand for animal products in the United States, corn for grain and various forage crops, (all of which is transferred into animal feed) account for an aggregate average of 50% of all irrigated crop acres (USDA, 2018). This shows the current heavy water and land dependency in the United States on the production of animal feed with more than 35% of the corn grown in the United States being used for animal feed (Leff et al., 2004; Foley, 2013). This is to say that much of the water consumption due to animal agriculture can be reduced by minimizing various inefficiencies in its implementation. Strategic crop selection for feed, appropriate land allocation, and diet restrictions are all prominent ways to reduce the water footprint of animal agriculture and still balance both land and energy requirements calculated in an LCA. This applied overview of the system provides a more comprehensive approach to sustainability in food production for all food products.

Food manufacturing and production

According to the Centers for Disease Control and Prevention (CDC) within the U.S. Department of Health and Human Services, groundwater is considered one of the safest sources of water and, consequently, 68% of irrigation systems utilize this resource. However, water used for irrigation may be obtained from multiple sources, and as shown, may be applied through various irrigation systems. In the majority of instances, water quality varies greatly because there is no set standard of water testing for agricultural producers. This concern regarding the water quality used to grow fresh produce directly affects the introduction of possible foodborne pathogens (Bihn et al., 2013). In addition, there are currently no national quality standards for surface water used in the production of fresh produce. Although many users have adopted the EPA Ambient Water Quality Standards, there remains a lack of standardized application that increases the risk of possible foodborne illness (Bihn et al., 2013). This water quality not only affects the food supply, but it also has direct ecological impacts on local watersheds with pathogen introduction through runoff. In fact, little data is available on the transport and survival of pathogens in agricultural production because of the grand scale of application, and tracking the potential pathogenic introduction from runoff water through various soil layers and eventual percolation into groundwater (Bradford et al., 2013). In one producer survey, 85% reported that they use an overhead sprinkler system as their primary or only water delivery method. The FDA has identified crops in this category, irrigated with overhead sprinkler systems, as high risk and includes berries, green onions, herbs, leafy greens, netted melons, tomatoes, apples, beans, beets, broccoli, cauliflower, corn, cucumbers, eggplant, garlic, pears, peppers, potatoes, shallots, smooth melons, and squash (Bihn et al., 2013). Despite the known risks, requiring producers to test their water sources and application water requires an additional agricultural step that costs both time and equipment investments.

Food processing and manufacturing accounts for 5-10% of water consumption in the United States (Meneses et al., 2017). Water use in these industries has more significance than suggested by its consumption rate because it has a direct effect on the national food supply and generates significant volumes of wastewater. Currently, regulations require that potable water quality standards must be used for food contact applications. To compensate for no standardized irrigation water, strict requirements for water input quality in food manufacturing and effluent wastewater disposal impose significant financial burdens on the industry. These operations compete with local communities for natural resources, and as water becomes scarcer, environmental regulations become more stringent, and wastewater treatment becomes more expensive, businesses are motivated to look at alternative ways to produce food with more sustainable water management (Mavrov et al., 2000). Different food sectors produce wastewater of varying qualities, but for all cases water reconditioning and reuse offer the opportunity to reduce water consumption and to contribute to better water management in the food processing industry (Meneses et al., 2017). Poultry processing uses about 26.5 liters of water per bird during primary and secondary washing of live birds (Avula et al., 2009). Processors are required to remove the majority of particulates prior to plant discharge because the amount of organic matter creates a high chemical oxygen demand (COD) and biological oxygen demand (BOD). Treatment and recycling options using membrane filtration have been explored throughout the industry to reduce both water consumption and operating costs (Avula et al., 2009). Similarly, membrane filtration is a researched option for the dairy industry. It has been found that the retentate (concentrated flow that does not pass through the membrane) from dairy water processing could potentially be used as a value-added product in the manufacturing of biofuels (Luo et al., 2011). In the aquaculture industry, the recycling of excess fish nutrients can be used as potential biomass and several research studies have been conducted to find the optimal crops for aquaculture greywater denitrification. Using particular crop varieties with an appropriate scale of operation, it has been found that this conversion of nutrients to biomass can be profitable for the industry (Graber et al., 2009). With vegetable wash water, it has been found that treatment options like ozonation and UV-C light treatments can allow for less frequent changing of spent water and less sanitizer discharge in vegetable wash effluent (Selma et al., 2008).

Advancements in technology allow for a myriad of cost-effective possibilities throughout the food manufacturing industry for conserving and recycling water. In any water reconditioning operation, continuous monitoring, audits, and frequent sampling of the water are required (Meneses et al., 2017). In some processes, wastewater reuse may not only be ecologically beneficial, but economically advantageous as well. The economic benefits of any particular operation depends on the level of microbial and chemical contamination, cost of available technologies, and the amount of processing required to produce potable water (Mavrov et al., 2000). Such economically viable conditions with minimal required reconditioning have been found in areas such as processing of cheese whey, condensing evaporative water, plastic bottle wash water, poultry water, final produce rinse water, and fresh cut vegetable processing, to only name a few (Meneses et al., 2017; Mavrov et al., 2000).

Unfortunately, there are limited publications detailing with scientific data around using reconditioned water in food manufacturing. This is largely due to the potable water quality, risk perceptions, available technologies and initial equipment costs, and food safety considerations (Meneses et al., 2017). Another hurdle in assessing the data for privatized water reconditioning in specific processes is obtaining commercially privileged information that is not openly available from the U.S. food industry. This limitation significantly slows the implementation of new technologies in these various operations (Meneses et al., 2017). Finally, businesses would need to consider the costs of a water reclamation system and monitoring water quality parameters. Water quality assessment includes the monitoring of COD, BOD, total organic carbon (TOC), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia, nitrate, nitrite, pH, conductivity, aerobic plate counts (APC), and coliforms (Meneses et al., 2017). These parameters are similar to those considered in the public assessment of wastewater discharges and all would generally be considered in potable water determinations.

Conclusions

The scientific data show that freshwater supplies across the United States are being depleted from mismanaged overuse and pollution. As resources degrade or become scarce, competition will increase, which increases the likelihood of water conflicts. Successful water management practices are embedded within the broader context of social, economic, and political challenges (U.S. Government Global Water Strategy, 2017). Continuous scientific monitoring on a broad scale through initiatives like the GRACE satellites and USGS hydrological surveying are paramount to understanding the efficacy of new technologies. Internationally, businesses are incorporating an estimated water footprint into their annual environmental report, labeling products with their water impact, and looking to create a certification process for water conservation (Hoekstra, 2012). There needs to be a continued investment in sustainable infrastructure and innovations for irrigated agriculture from both the producer and the appropriate governmental agencies. Instead of supplementing a cheap supply water to sustain a depleting resource, they should look to invest and subsidize those farms that have implemented tangible conservation efforts, eliminating the financial burden to the producer of self-inflicted unilateral economic disarmament that coincides with reduced water usage. Environmental protection from both agricultural runoff and land repurposing should proactively shift from responding to incidents of degradation to investing remediation monies in minimizing initial ecological destruction. There is not one 'right' solution to water management. However, intelligent and strategic scientific monitoring of the flow of agricultural water, improved efficiency of current irrigation systems (micro-irrigation), crop selection, appointment of a more apolitical technocratic form of water governance, and utilization of wastewater and water recovery systems, are all possibilities that need to be explored based on local water concerns. As an example of a water abundant country, Israel thrives despite its desert location by intelligently utilizing almost 95% of its wastewater supply (Siegel, 2015). To alleviate the demand for the current water supply, alternate innovations such as managed aquifer recharge, infrastructure improvement, and seawater desalination options need to be applied in the appropriate locations, with an accurate LCA analyzation of their economic and ecological benefits. Direct water and food management in farming operations like urban farming, hydroponics, and aquaculture need to be explored further to more responsibly account for increasing water and food supply. As much as water scarcity can be a source of conflict, water abundance can be a source of conflict resolution, with countries collaborating internationally to alleviate water scarcity. There needs to be a culture and ethos developed in the United States centered around awareness and water conservation reflected in diet choices, implemented technology and research, the education system, and governmental policy. Treating water as a finite value-added food ingredient is paramount to the success of the global food supply with significant economical, ecological, and social impact.

References

Avula, R., Nelson, H., Singh, R., (Jan. 2009). Recycling of poultry process wastewater by ultrafiltration. *Innovative Food Science and Emerging Technologies*, 10(1); 1-8.

Berndt, M., Katz, B., Kingsbury, J., Crandall, C., (2014). The quality of our nation's waters: The quality in the Upper Floridan Aquifer and overlaying surficial aquifers, southeastern United States, 1993-2010. *U.S. Department of the Interior, U.S. Geological Survey*. Reston, VA. Circular 1355.

Bihn, E., Smart, C., Hoeptig, C., Worobo, R., (Oct. 2013). Use of surface water in the production of fresh fruits and vegetables: A survey of fresh produce growers and their water management practices. *Food Protection Trends*, 33(5); 307-314.

Boland, M., Rae, A., Vereijken, M., Mewwissen, M., Fischer, A., Van Boekel, M., Ruthrford, S., Gruppen, H., Moughan, P., Hendriks, W., (Jan. 2013). The future supply of animal-derived protein for human consumption. *Trends in Food Science and Technology*, 29(1); 62-73.

Bradford, S., Morales, V., Zhang, W., Harvey, R., Packman, A., Mohanram, A., Welty, C., (2013). Transport and fate of microbial pathogens in agricultural settings. *Critical Reviews in Environment Science and Technology*, 43; 775-893.

Chandel, M., Pratson, L., Jackson, R., (Oct. 2011). The potential impacts of climate-change policy on freshwater use in thermoelectric power generation. *Journal of Energy Policy*, 39(10); 6234-6243.

Culp, P., Glennon, R., (Oct. 6-7, 2012). Parched in the west, but shipping water to China, bale by bale. *The Wall Street Journal*. 1-3.

Dalin, C., Wada, Y., Kastner, T., Puma, M., (Mar. 2017). Groundwater depletion embedded in international food trade. *Nature*, 543; 700-704.

Desimone, L., McMahon, P., Rosen, M., (Jan. 2015). The quality of our nation's waters: Water quality in principal aquifers of the United States, 1991-2010. *U.S. Department of the Interior, U.S. Geological Survey*. Reston, VA. Circular 1360.

Dillon, P., Pavelic, P., Page, D., Beringen, H., Ward, J., (Feb. 2009). Managed aquifer recharge: An introduction. *Australian Government, The National Water Commission*. 13. Accessed July 25, 2018, from https://recharge.iah.org/files/2016/11/MAR_Intro-Waterlines-2009.pdf

Edwards, C., Hill, P., (Feb. 1, 2012). Cutting the Bureau of Reclamation and reforming water markets. *The Cato Institute, Downsizing the Federal Government*. 1-26.

Elfers, S., James, I., (Dec. 2015). Pumped dry: A race to the bottom of the Ogallala in Kansas [video]. *USA Today*. Accessed July 25, 2018, from https://www.usatoday.com/pages/interactives/groundwater/

Elfers, S., James, I., (Dec. 2015). Pumped dry: Dry wells, sinking ground in California [video]. *USA Today*. Accessed July 25, 2018, from https://www.usatoday.com/pages/interactives/groundwater/

Elimelech, M., Phillip, W., (Aug. 2011). The future of seawater desalination: Energy, technology and the environment. *Science*, 333(6043); 712-717.

Fagin, D., (Mar. 2013). *Toms River: A story of science and salvation*. New York City, United States. Bantam Books.

Famiglietti, J., Rodell, M., (June 2013). Water in the balance. *Science*, 340(6138); 1300-1301.

Foley, J., (Mar. 5, 2013). It's time to rethink America's corn system. *Scientific American.* 1-14.

Food and Agriculture Organization of the United Nations (FAO). (2011). *The state of food and agriculture: Women in agriculture- closing the gender gap for development*. Rome, Italy. Accessed July 25, 2018, from http://www.fao.org/docrep/013/i2050e/i2050e.pdf

Food and Agriculture Organization of the United Nations (FAO). (2014). *The state of food and agriculture- Innovation in family farming*. Rome, Italy. Accessed July 25, 2018, from http://www.fao.org/3/a-i4040e.pdf

Glennon, R., (Mar. 2009). *Unquenchable: America's water crisis and what to do about it*. Washington D.C., United States. Island Press.

Graber, A., Junge, R., (Sept. 2009). Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination*, 246(1-3); 147-156.

Greenburg, P., (June 2010). *Four fish: The future of the last wild food*. London, United Kingdom. Penguin Press.

Hanjra, M., Qureshi, M., (Oct. 2010). Global water crisis and the future of food security in an era of climate change. *Food Policy Journal,* 35(5); 365-377.

Hanson, B., May, D., (July 2004). Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. *Agricultural Water Management*, 68(1); 1-17.

Hoekstra, A., (April 2012). The hidden water resource use behind meat and dairy. *Animal Frontiers*, 2(2); 1-6.

Howitt, R., Medellin-Azuara, J., MacEwan, D., Lund, J., Sumner, D., (July 2014). Economic analysis of the 2014 drought for California Agriculture. *University of California, Davis, Center for Watershed Sciences, ERA Economics*. 1-27.

Kearney, M., Harris, B., Hershhein, B., Jacome, E., Nantz, G., (Oct. 20, 2014). In times of drought: Nine economic facts about water in the United States. *The Hamilton Project*. 1-28.

Klopffer, W., (Dec. 1997). Life cycle assessment: From beginning to current state. *Environmental Science and Pollution Research*, 4(4); 223-228.

Leff, B., Ramankutty, N., Foley, J., (Jan. 2004). Geographic distribution of major crops across the world. *Global Biogeochemical Cycles,* 18(1); 1-46.

Long, D., Scanlon, B., Longuevergne, L., Sun, A., Fernando, D., Save, H., (July 2013). GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas. *Geophysical Research Letters*, 40(13); 1-14.

Luo, J., Ding, L., Qi, B., Jaffrin, M., Wan, Y., (Aug. 2011). A two-stage ultrafiltration and nanofiltration process for recycling dairy wastewater. *Bioresource Technology*, 102(16); 7437-7442.

Maupin, M., Kenny, J., Hutson, S., Lovelace, J., Barber, N., Linsey, K., (Nov. 2014). Estimated use of water in the United States in 2010. *U.S. Department of the Interior, U.S. Geological Survey*. Reston, VA, Circular 1405.

Mavrov, V., Belieres, E., (Dec. 2000). Reduction of water consumption and wastewater quantities in the food industry by water recycling using membrane processes. *Desalination*, 131; 75-86.

McMaken, R., (Oct. 28, 2013). Water subsidies and shortages in the American west. *Mises Daily Articles.*

Meneses, Y., Stratton, J., Flores, R., (Mar. 2017). Water reconditioning and reuse in the food processing industry: Current situations and challenges. *Trends in Food Science and Technology*, 61; 62-69.

Pan, S. Y., Snyder, S., Packman, A., Lin, Y., Chiang, P. C., (April 2018). Cooling water use in thermoelectric power generation and its associated challenges for addressing water-energy nexus. *Water-Energy Nexus*. 1; 1-16.

Poore, J., Nemecek, T., (June 2018). Reducing food’s environmental impacts through producers and consumers. *Science*, 360(6392); 987-992.

Reisner, M., (1986). *Cadillac desert: The American west and its disappearing water*. London, United Kingdom. Penguin Press.

Richey, A., Thomas, B., Lo, M., Reager, J., Famiglietti, J., Voss, K., Swenson, S., Rodell, M., (July 2015). Quantifying renewable groundwater stress with GRACE. *Water Resources Research*, 51(7); 1-34.

Rodell, M., Famiglietti, J., (June 2002). The potential for satellite-based monitoring of groundwater storage changes using GRACE: The High Plains Aquifer, Central US. *Journal of Hydrology*, 263(1-4); 245-256.

Selma, M., Allende, A., Lopez-Galvez, F., Conesa, M., Gil, M., (Sept. 2008). Disinfection potential of ozone, ultraviolet-C and their combination in wash water for the fresh-cut vegetable industry. *Food Microbiology*, 25(6); 809-814.

Siegel, S., (Sept. 2015). *Let there be water: Israel's solution for a water-starved world*. New York City, United States. St. Martin's Press.

Tenne, A., Water Authority, State of Israel Desalination Division, (Oct. 2010). *Sea water desalination in Israel: Planning, coping with difficulties, and economic aspects of long-term risks*. Accessed July 25, 2018, from http://www.water.gov.il/Hebrew/ProfessionalInfoAndData/2012/12-Desalination-in-Israel.pdf

United Nations Economic and Social Affairs. (Jan. 2003). *Substantive issues arising in the implementation of the international covenant on economic, social, and cultural rights*. Geneva, Switzerland. Accessed July 24, 2018, from http://www2.ohchr.org/english/issues/water/docs/CESCR_GC_15.pdf

United Nations Department of Economic and Social Affairs. (Oct. 2014). *International decade for action 'Water for Life' 2005-2015*. Geneva, Switzerland. Accessed on July 25, 2018, from http://www.un.org/waterforlifedecade/food_security.shtml

U.S. Department of Agriculture (USDA). (July 2018). *Irrigation and water use*. Accessed July 25, 2018, from https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use.aspx

U.S. Department of the Interior, Bureau of Reclamation. (Mar. 2016). *SECURE Water Act section 9503(c) - Reclamation climate change and water 2016*. Prepared for the United States Congress. Denver, Colorado. Accessed on July 25, 2018, from https://www.usbr.gov/climate/secure/docs/2016secure/2016SECUREReport.pdf

U.S. Department of State, Bureau of Oceans and International Environmental and Scientific Affairs. (Nov. 2017). *U.S. Government Global Water Strategy 2017*. Accessed July 25, 2018, from https://www.state.gov/documents/organization/275842.pdf

U.S. Department of the Interior, U.S. Geological Survey. (April 2017). *Water science glossary of terms*. Accessed July 25, 2018, from https://water.usgs.gov/edu/dictionary.html

U.S. Health and Human Services, Centers for Disease Control and Prevention. (Oct. 2016). *Other uses and types of water: Agricultural water*. Atlanta, Georgia. Accessed on July 25, 2018, from https://www.cdc.gov/healthywater/other/agricultural/index.html#

Wan, L., Cai, W., Jiang, Y., Wang, C., (July 2016). Impacts on water-quality induced scarcity: Drivers of nitrogen related water pollution transfer under globalization from 1995-2009. *Environmental Research Letters*, 11(7); 1-23.

World Health Organization (WHO) and the United Nations Children's Fund (UNICEF). (July 2017). *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines*. Geneva, Switzerland. Accessed July 24, 2018, from http://www.who.int/mediacentre/news/releases/2017/launch-version-report-jmp-water-sanitation-hygiene.pdf.